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SESSION ID: BR-W09

That's Not My Signature! Fail-Stop Signatures for a Post-Quantum World

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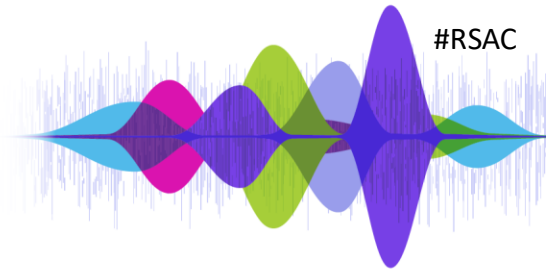

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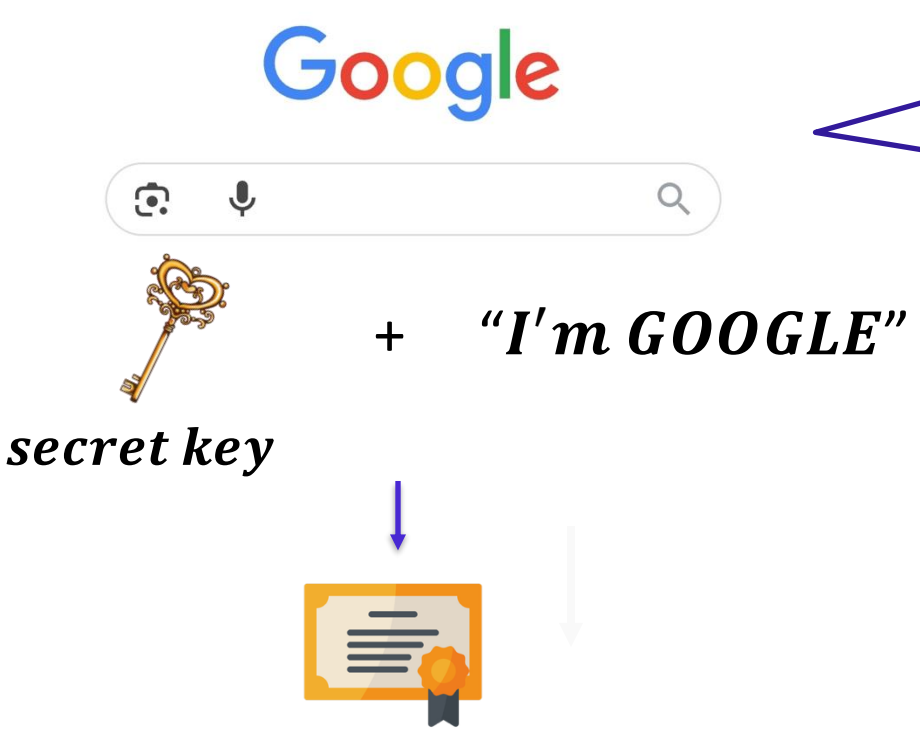
Digital Signatures

- Digital signature allows verification of:
  - The **content** of a message
  - The **identity** of the signer



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Weaponizing Signatures

- In 2011, forged certificates signed by **DigiNotar** exploited for MiTM attacks against Gmail users in Iran

Weaponizing Signatures

- In 2012, forged signatures signed by **Microsoft** exploited by the **Flame** malware for a large scale cyber-espionage and sabotage campaign

Weaponizing Signatures

- **Two signature forgery attacks, but are they the same?**

DigiNotar®
A VASCO COMPANY

https://

Google

Compromising **secret key**

DigiNotar attack [2011]:

Cyber attack: Hackers gained **internal access**

Compromising **secret key**

Breaking the cryptographic **primitive**

DigiNotar attack [2011]:

Cyber attack: Hackers gained **internal access**

Flame attack [2012]:

Cryptanalytic attack: Hackers broke the **MD5 cryptographic primitive**

Compromising **secret key**

Breaking the cryptographic **primitive**

DigiNotar attack [2011]:

Cyber attack: Hackers gained **internal access**

DigiNotar cannot be trusted!!!

Compromising **secret key**

Breaking the cryptographic **primitive**

MD5 is broken!!!

Flame attack [2012]: Cryptanalytic attack: Hackers broke the **MD5 cryptographic primitive**

Compromising **secret key**

Breaking the cryptographic **primitive**

It is crucial to distinguish between the attacks!

However, this is not currently possible with modern digital signature schemes

Nigel Smart
26 mins ·

Quantum update. LWE is definitely still alive. Or at least still alive until someone opens the box.

CRYPTOMATHiC

WHY CRYPTOMATHIC? WHAT WE OFFER ABOUT INSIGHTS CONTACT

4 MIN READ

NIST PQC FINALISTS UPDATE: IT'S OVER FOR THE RAINBOW

Edlyn Teske : 26. March 2022

Quantum Computing Report
Where Qubits Entangle with Commerce

NIST PQC Round 4 Candidate SIKE May Have Been Broken

We reported last month that NIST had selected four Post-
Round 3 and another four algorithms were selecte

Breaking Rainbow Takes a Weekend on a Laptop

Ward Beullens

IBM Research, Zurich, Switzerland
wbe@zurich.ibm.com

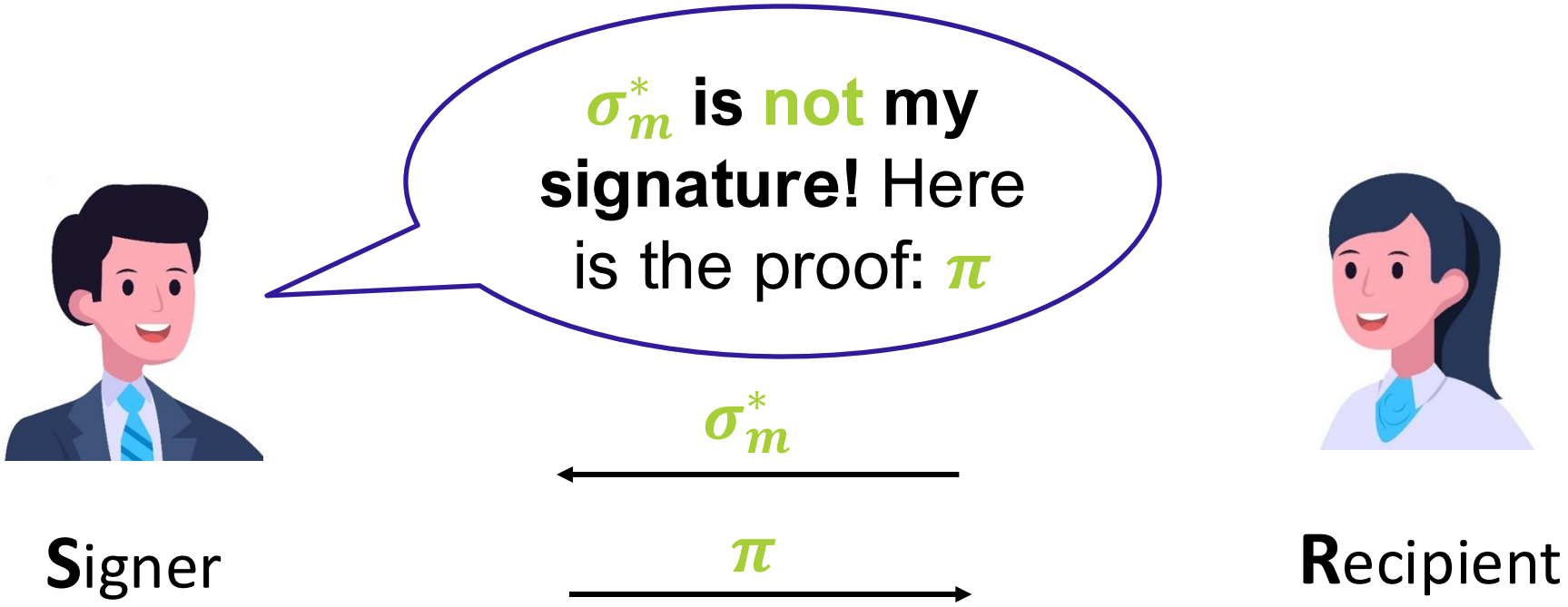
against the
t signature
dardization
s for all the

The next breakthrough may not be published…

If a **digital signature** is **broken**,
and a forgery was created,
can we **identify** this?

Fail-Stop Signature (FSS)

- **Fail-Stop Signature** [PW89] has a "**forgery detection**" procedure



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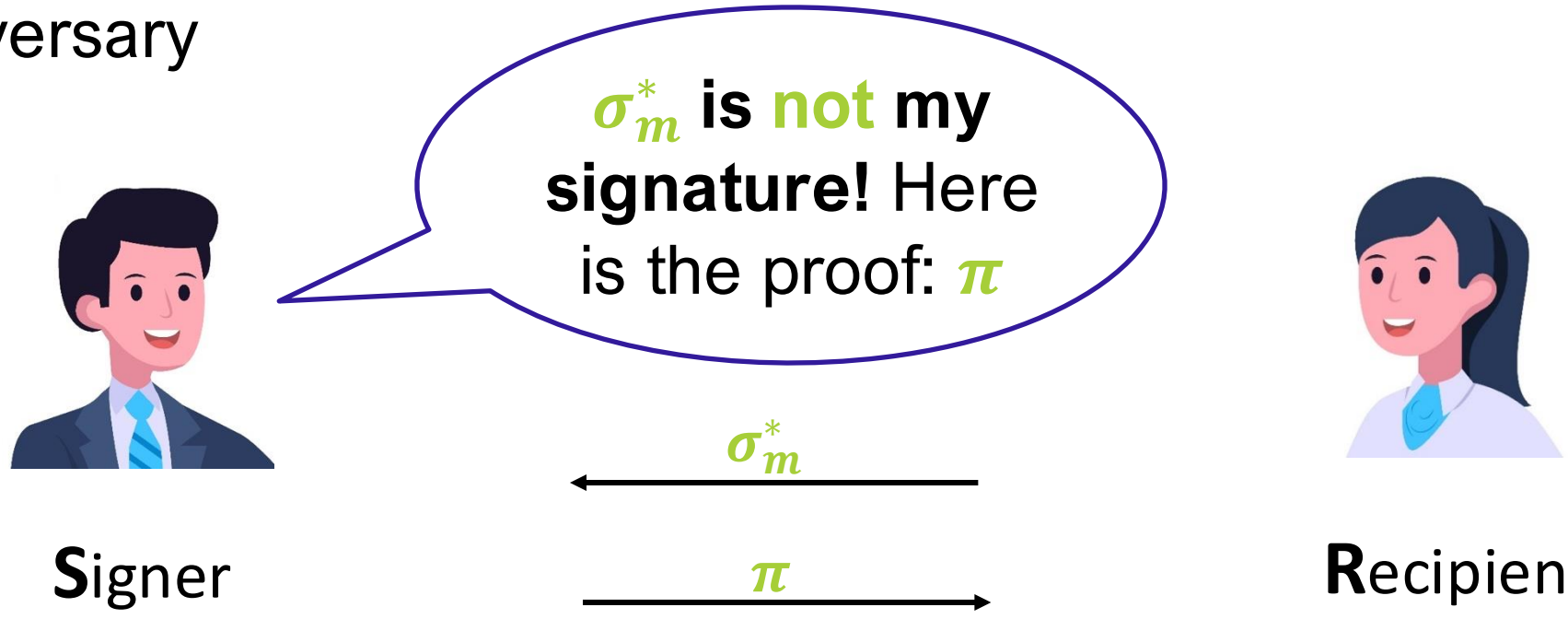
Fail-Stop Signature (FSS)

- We can prove a forgery has occurred
- We cannot take back a signature
- Unbounded adversary

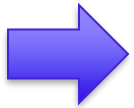


Related Works

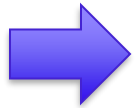
- Lower bounds on FSS [**H**eijst**P**edersen**P**fitzmann**93**]
- Constructions based on standard assumptions (Factoring, RSA, OWF, etc.): [**H**eyst**P**edersen92, **D**amgard**P**edersen**P**fitzmann**94**, **B**ari**P**fitzmann**97**, **S**afavi-**N**aini**S**usilo**W**ang**20**]
- Proof-of-forgery for hash-based signature [**K**iktenko**K**udinov**B**ulychev**F**edorov**21**]

Our Work: Fail-Stop for a Post-Quantum World

Fail-Stop Signature [PW89] **Unbounded adversaries**

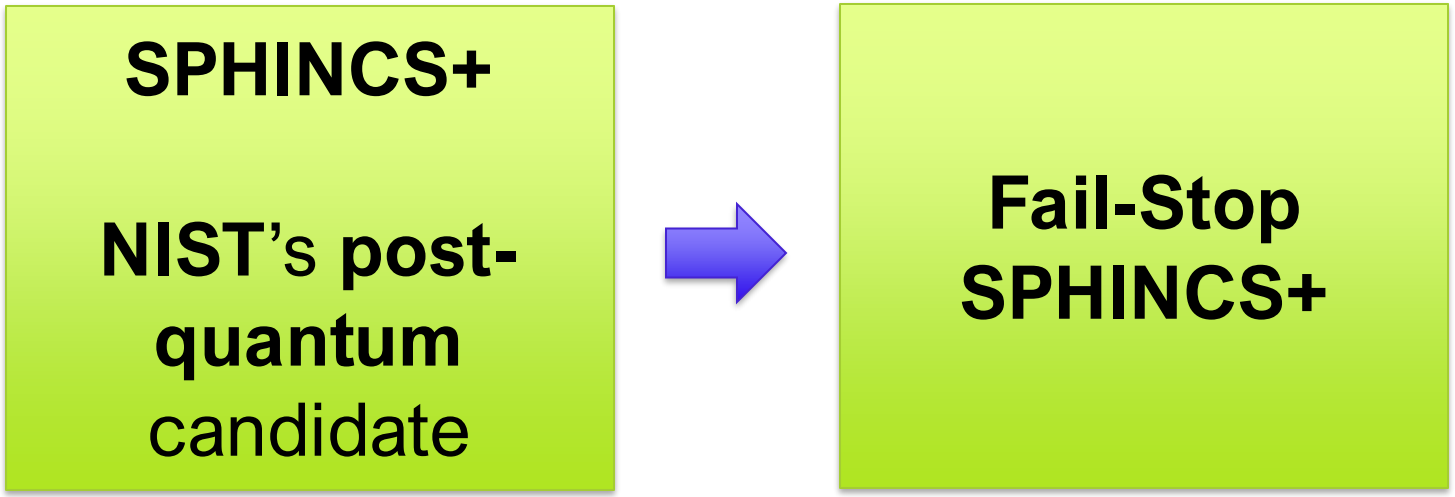


Introduce the "**fine-grained** adversarial model"



Fail-Stop Signature **Powerful but bounded adversaries**

Our Construction



- SPHINCS+ has Lamport signature as basic structure

Lamport One-Time Signature

- The **security** **assumption**: one way function $\boldsymbol{h}$: $\{0,1\}^{\mathbf{128}} \rightarrow \{0,1\}^{\mathbf{128}}$
- Message: 0 or 1

Signer

(r_0, r_1)

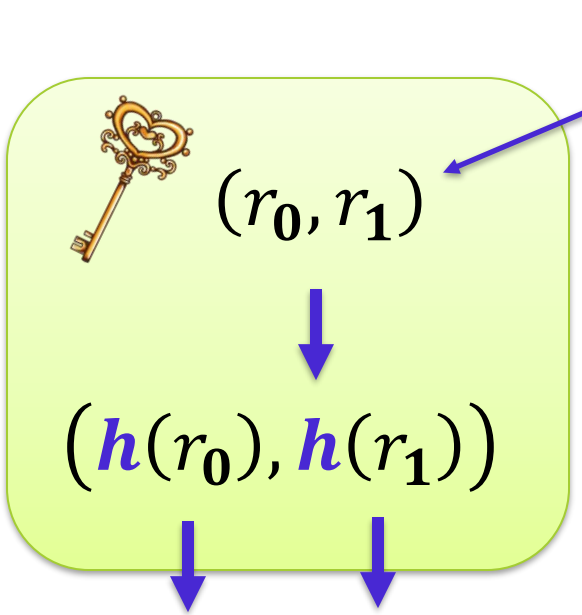
$\boldsymbol{sk}$

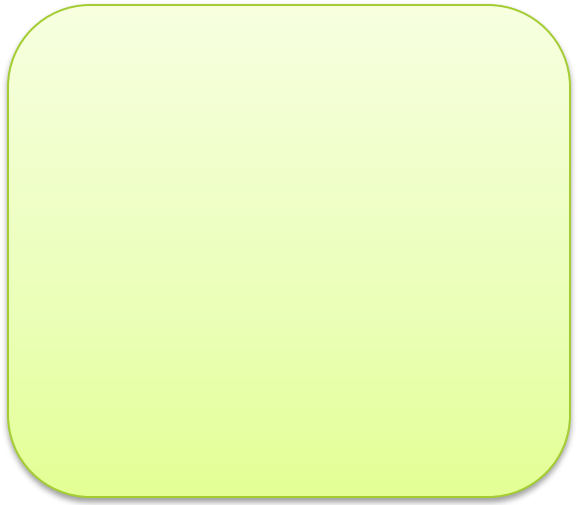
Recipient

Lamport One-Time Signature

- The **security** **assumption**: one way function $\boldsymbol{h}: \{0,1\}^{\mathbf{128}} \rightarrow \{0,1\}^{\mathbf{128}}$
- Message: 0 or 1

Signer





Recipient

Lamport One-Time Signature

- The **security** **assumption**: one way function $\boldsymbol{h}: \{0,1\}^{\mathbf{128}} \rightarrow \{0,1\}^{\mathbf{128}}$
- Message: 0 or 1

Signer

(r_0, r_1)

$(h(r_0), h(r_1))$

(vk_0, vk_1)

message:

$\mathbf{0/1}$ **signature**

$\sigma_b = (b, r_b)$

Recipient

Lamport One-Time Signature

- The **security** **assumption**: one way function $\boldsymbol{h}: \{0,1\}^{\mathbf{128}} \rightarrow \{0,1\}^{\mathbf{128}}$
- Message: 0 or 1

Signer

(r_0, r_1)

$\big(h(r_0), h(r_1)\big)$

(vk_0, vk_1)

message:

0/1 **signature**

$\sigma_b = (b, r_b)$

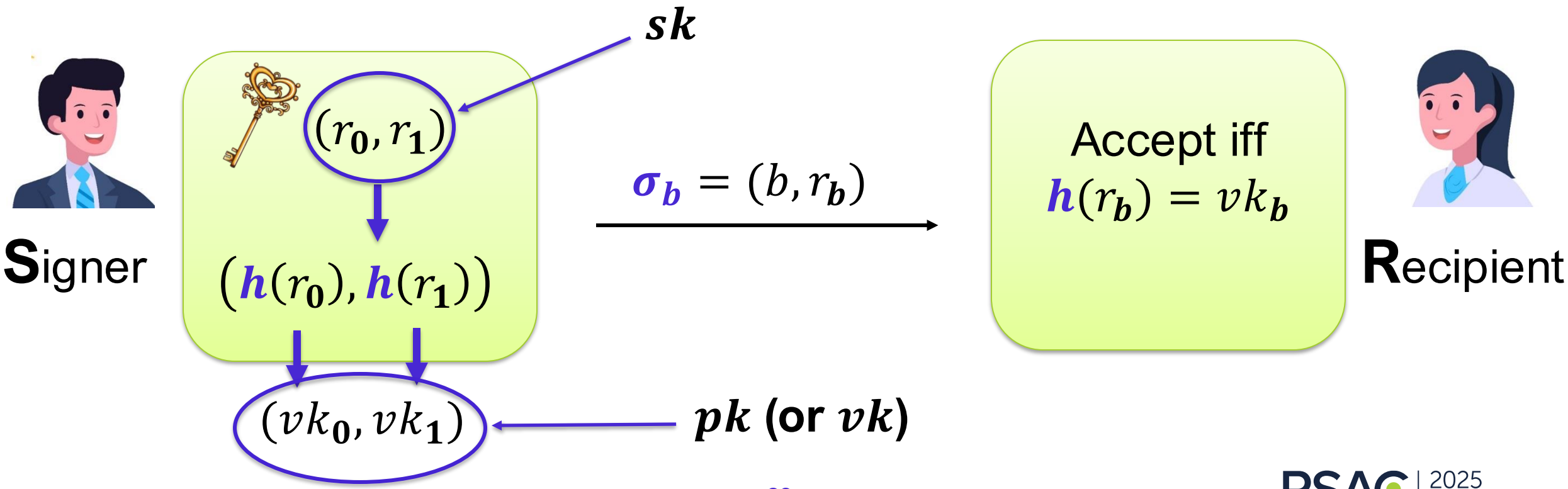
Accept iff

$h(r_b) = vk_b$

Recipient

Lamport One-Time Signature

- **Necessary condition for FSS:** each vk corresponds to **multiple** sk



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Lamport One-Time Signature

- **[KKBF21]**: use a compressing $h: \{0,1\}^{128+c} \to \{0,1\}^{128}$

$$expect\ \sim 2^c\ r^*\ such\ that\ h(r^*) = h(r)\ for\ every\ r$$

Signer

(r_0, r_1)

$\downarrow$

$(h(r_0), h(r_1))$

$\downarrow \quad \downarrow$

(vk_0, vk_1)

$\sigma_b = (b, r_b)$ $\longrightarrow$

Accept iff
$h(r_b) = vk_b$

Recipient

Lamport One-Time Signature

- What is the **proof-of-forgery?**

Signer

(r_0, r_1)

$\downarrow$

$(h(r_0), h(r_1))$

$\downarrow \quad \downarrow$

(vk_0, vk_1)

$\sigma_b = (b, r_b)$ $\longrightarrow$

Accept iff
$h(r_b) = vk_b$

Recipient

Lamport Fail-Stop Signature

- **Collision-resistance (CRH)** hash function:

$$\boldsymbol{h}: \{0,1\}^{\mathbf{128}+c} \rightarrow \{0,1\}^{\mathbf{128}}$$

- It is hard for a **PPT** adversary $\boldsymbol{A}$ to find two different x_0, x_1 such that

$$x_0 \neq x_1,$$

$$\boldsymbol{h}(x_0) = \boldsymbol{h}(x_1)$$

Lamport Fail-Stop Signature

- Use a **compressing-collision-resistance** $h: \{0,1\}^{128+c} \rightarrow \{0,1\}^{128}$

Signer

(r_0, r_1)

$\downarrow$

$(h(r_0), h(r_1))$

$\downarrow \quad \downarrow$

(vk_0, vk_1)

$\sigma_b = (b, r_b)$ $\longrightarrow$

Accept iff
$h(r_b) = vk_b$

Recipient

Lamport Fail-Stop Signature

$\sigma_b^* = (b, r_b^*)$

Adversary

Signer

(r_0, r_1)

$(h(r_0), h(r_1))$

(vk_0, vk_1)

Recipient

Lamport Fail-Stop Signature

Adversary

$\sigma_b^* = (b, r_b^*)$

Signer

(r_0, r_1)

$(h(r_0), h(r_1))$

(vk_0, vk_1)

σ_b^*

$h(r_b^*) = vk_b$

Accept

Recipient

Lamport Fail-Stop Signature

Adversary

$\sigma_b^* = (b, r_b^*)$

Signer

(r_0, r_1)

$\downarrow$

$(h(r_0), h(r_1))$

$\downarrow \quad \downarrow$

(vk_0, vk_1)

$\sigma_b^* = (b, r_b^*)$

σ_b^*

$\downarrow$

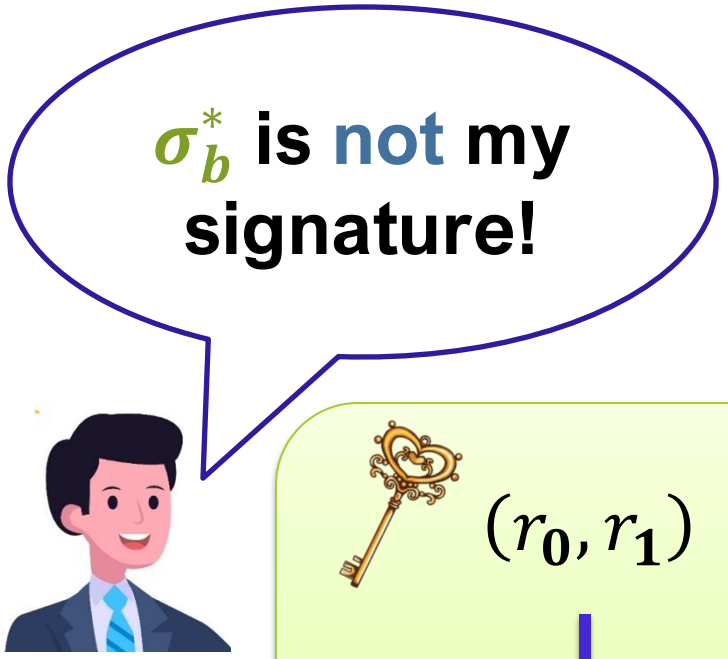
$h(r_b^*) = vk_b$

$\downarrow$

Accept

Recipient

Lamport Fail-Stop Signature



Adversary

$\sigma_b^* = (b, r_b^*)$

Signer

(r_0, r_1)

$\downarrow$

$(h(r_0), h(r_1))$

$\downarrow \quad \downarrow$

(vk_0, vk_1)

$\sigma_b^* = (b, r_b^*)$

σ_b^*

$\downarrow$

$h(r_b^*) = vk_b$

$\downarrow$

Accept

Recipient

Lamport Fail-Stop Signature

Signer

Here is the proof:

Adversary

$\sigma_b^* = (b, r_b^*)$

(r_0, r_1)

$(h(r_0), h(r_1))$

(vk_0, vk_1)

$\sigma_b^* = (b, r_b^*)$

$\pi = (r_b, r_b^*)$

Recipient

Lamport Fail-Stop Signature

Here is the proof:

Adversary

$\sigma_b^* = (b, r_b^*)$

Signer

(r_0, r_1)

$(h(r_0), h(r_1))$

(vk_0, vk_1)

$\sigma_b^* = (b, r_b^*)$

$\pi = (r_b, r_b^*)$

Check

$h(r_b) = h(r_b^*)$

$r_b \neq r_b^*$

Accept

Recipient

Lamport Fail-Stop Signature

- The proof-of-forgery is a **collision** on h

Signer

(r_0, r_1)

$\downarrow$

$(h(r_0), h(r_1))$

$\downarrow \quad \downarrow$

(vk_0, vk_1)

$\sigma_b^* = (b, r_b^*)$

$\pi = (r_b, r_b^*)$

Check

$h(r_b) = h(r_b^*)$

$r_b \neq r_b^*$

$\downarrow$

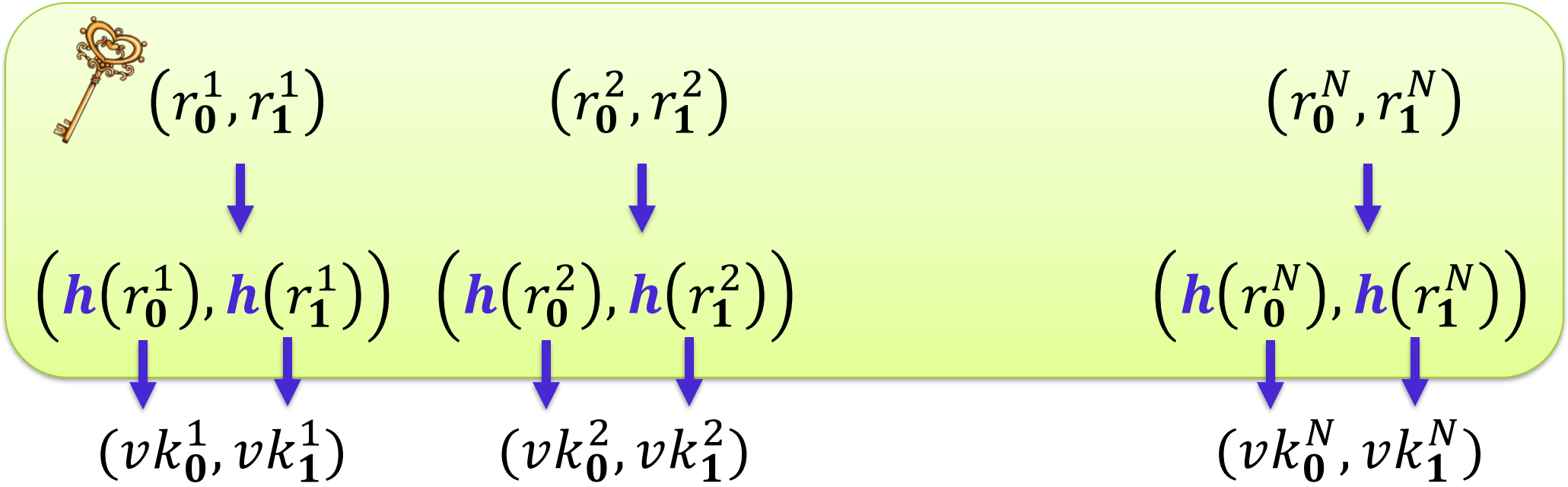
Accept

Recipient

Extending Lamport to Multiple-Use

- We want to sign on N bits
- Secret keys: (r_0^1, r_1^1),..., (r_0^N, r_1^N)

Signer



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Extending Lamport to Multiple-Use

- The signer computes the pairs of secret keys (r_0^i, r_1^i) from the $\boldsymbol{Seed}$
- Secret keys: $\boldsymbol{Seed}$

Signer

$(vk_0^1, vk_1^1), \ldots, (vk_0^N, vk_1^N)$

Security Against Unbounded Adversaries

- We have only **one** **secret key** – the **seed**
- An **unbounded** **adversary** can **find** it!!

Signer

$(vk_0^1, vk_1^1), \ldots, (vk_0^N, vk_1^N)$

Challenges: Efficiency

- Fail-stop signatures assume **unbounded** adversaries, but this **prevents** us from constructing a **practical** fail-stop signature for **SPHINCS+**
- We introduce a new assumption inspired by **real-world risk** management practices against **adversaries**

“Fine-Grained” Adversarial Model

- **NIST** assumes that there are **different levels** of **adversaries**
- We **pay** in **efficiency** to **protect** against more **powerful adversaries**

	bit security	**signature (bytes)**
SPHINCS+-128s	128	7856
SPHINCS+-192s	192	16,224
SPHINCS+-256s	256	29,792

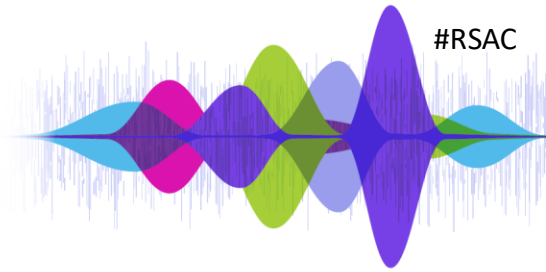
Our Results: Fail-Stop SPHINCS+

FSS.SPHINCS+ 128 bit with **256** bits of “fail-stop” security

is **smaller** and **faster** than **SPHINCS+ 256** bit

	pk (bytes)	sk (bytes)	sig (bytes)	Bit Sec Recipient	Bit Sec Signer
SPHINCS$^+$-128s	32	64	7856	128	128
FSS.SPHINCS-128s,$c_s = 2$ (log)	32	96	11,790	128	256
FSS.SPHINCS-128s,$c_s = 2$ (c_s sigs)	32	96	23,580	128	256
SPHINCS$^+$-256s	64	128	29,792	256	256

Summary



- We introduce fail-stop signatures to a post-quantum world
- We introduce the **“fine-grained”** adversarial model
- Our model allows us to **upgrade** the **security** while keeping **efficiency**

Pay a little now

You never know when your scheme might be broken

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One Community.

Thank you!

For more information:

https://eprint.iacr.org/2023/1754